ONR Postdoctoral Fellowship: Geoacoustic Inversion and Source Localization in a Randomly Fluctuating Shallow Water Environment

Ying-Tsong Lin
MS#11, Woods Hole Oceanographic Institution
Woods Hole, MA 02543
phone: (508) 289-2329 fax: (508) 457-2194 email: ytlin@whoi.edu

Award Number: N00014-08-1-0204

LONG-TERM GOALS

The long-term goal of this project is to understand and mitigate the uncertainties of shallow-water acoustic inversions caused by strong oceanic temporal and spatial variability. To achieve this goal, we need to investigate the connection between acoustic signal fluctuations and the water-column variability, and further incorporate this connection into the acoustic inversions for increasing the inversion performance.

OBJECTIVES

The scientific objectives of this project are centered on improving acoustic inversions for estimating bottom properties and source position in a randomly fluctuating shallow-water ocean. The first objective is to develop and test a new data nullspace projection method to suppress the inversion errors caused by the random water-column fluctuations. This was accomplished in the first year of this project. The second year focused on developing a source localization technique. The acoustic and oceanographic data collected from the SW06 experiment [1], a multi-disciplinary experiment sponsored by the ONR and conducted on the Mid-Atlantic Bight continental shelf in 2006, were used to test the developed technique and also to study how water column variability negatively affects source range estimates. In addition to the source localization work, the PI also developed an empirical orthogonal function (EOF) fitting method to merge different data to estimate the full water-column sound speed profiles in the SW06 experiment. The goal of this last study is to provide a more complete oceanographic view of the local water-column variability to connect with the acoustic fluctuations seen in the data.

APPROACH

The data nullspace projection method was developed in the first year and was used in this project to reduce the inversion uncertainties caused by random water-column fluctuations. In the second year, a normal mode back-propagation approach was developed for passively localizing a remote sound source. The acoustic and oceanographic data collected from the SW06 experiment were used for testing this normal mode approach. In short, the approaches taken in this project involve theory, numerical calculation and experimental data analysis. The detailed explanations of the techniques developed are described in the next section, along with the work accomplished.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2009	**Annual**	**00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE
ONR Postdoctoral Fellowship: Geoacoustic Inversion And Source Localization In A Randomly Fluctuating Shallow Water Environment

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Woods Hole Oceanographic Institution,MS#11,Woods Hole,MA,02543

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Code 1 only

14. ABSTRACT
The long-term goal of this project is to understand and mitigate the uncertainties of shallow-water acoustic inversions caused by strong oceanic temporal and spatial variability. To achieve this goal, we need to investigate the connection between acoustic signal fluctuations and the water-column variability, and further incorporate this connection into the acoustic inversions for increasing the inversion performance.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**12**	

WORK COMPLETED

The tasks completed this year are itemized below.

1. Normal mode back-propagation approach for low-frequency broadband sound source localization

Acoustic normal modes are orthogonal bases to decompose a sound pressure field, and they have significant frequency dependence below few a hundred hertz in a typical continental shelf area (water depth ~ 100 m). Hence to properly decompose a sound pressure field, one needs to implement a broadband normal mode decomposition. The normal mode back-propagation approach for source localization utilizes one of the important properties of normal modes — modal dispersion; for a given mode, its modal phase and group speeds are dependent on the acoustic frequency. In general, the first step of this method is to implement a broadband mode filter to obtain individual modal arrivals. The second step is to back propagate the modal arrivals with their own speeds at the different frequencies. Finally, the source range estimate is found where the back-propagated modes align with each other.

2. SW06 experiment data analysis: U. Miami sound source localization

The normal mode approach described above has been tested by applying it to the acoustic data of known source position collected in the SW06 experiment. The sound source analyzed here is the U. Miami sound source (MSM), and it transmitted M-sequence phase encoded source signals at five different frequency bands (100, 200, 400, 800 and 1600 Hz) for nearly 4 weeks. In this work, the 100 Hz signal (25 Hz bandwidth) is selected. Every half an hour, a 1.5-min long transmission, which contained 36 identical M-sequence phase encoded signals, was emitted. With a matched filter, such encoded signals can be compressed, and a detailed modal arrival pattern is revealed, showing clearly that four modes arrived at the acoustic vertical hydrophone line arrays (VLA), see an example shown in Figure 1(a). Further implementing a least squares mode filter gives us excellent estimates of modal arrivals, see Figure 1(b).

To back-propagate the modal arrivals received at the VLA, one needs to calculate the theoretical modal speeds along the propagation path. In doing so, an environmental model is first reconstructed for the MSM source localization in this SW06 data analysis — this model has 3 range-independent water-column sound speed patches, accurate bathymetry, and tidal levels from data. Note that the range-independent sound speed patches are constructed using the water temperature measurements from the three moorings evenly distributed along the 19.74 km propagation path. After reconstructing the environment, the normal mode arrivals are back-propagated using a 25-m range interval with their own theoretical speeds calculated every 150 m. Two assumptions are given: 2-D in-plane propagation and no mode-coupling. An example of back-propagating to find the best source range estimate is shown in Figure 2.

An eight-day long time series of source range estimates are shown in Figure 3. Every half an hour, 35 M-sequence pulses are analyzed and 35 range estimates are obtained. The average value and standard deviation of these estimates are plotted. The total mean range estimate is 19.74 km for these 8-days data, which is the same as the true distance, along with a standard deviation of 570 m.

3. SW06 experiment data analysis: Sei whale localization

Comparatively little is known about sei whale (*Balaenoptera borealis*) vocalizations and behavior, and, in particular, very few recordings have been made in their presence in the Northwest Atlantic. A large number of sei whale calls were unexpectedly collected during the SW06 experiment, which introduced the first evidence of sei whales in this shallow water region. Using the normal mode approach developed in this project, we are able to precisely track the remote locations of these whales up to tens of kilometers. This part of work is a cooperative effort with Mr. Arthur E. Newhall at the Woods Hole Oceanographic Institution. See Figure 4 for an example of the whale tracking result.

4. Statistical merging of data sources to estimate full water-column sound speed in the SW06 experiment

A method for merging overlapping profile data sets into a single time series of profiles using an empirical orthogonal function (EOF) fitting technique was developed. The method was applied to data from the SW06 experiment. The sound speed profiles that result specify conditions for 43 days from the sea surface to the seafloor at the main VLA site. As shown in Figure 5, the temperature data collected on the main VLA, which covered depths of 13 m to the bottom, are merged with near-surface temperature data from a nearby surface spar buoy system. Temperature and salinity data collected on another nearby environmental mooring are used to estimate the water salinities on the array. For times after the measurements on the spar buoy and the environmental mooring are available, forecasts from the MIT Multidisciplinary Simulation, Estimation, and Assimilation System (MSEAS, [2]) are substituted in their place. The resultant sound speed profiles allow reliable acoustic propagation modeling, mode decomposition, and beamforming.

5. 3-D acoustic effects caused by nonlinear internal gravity waves

In addition to the acoustic inversion work, the PI also studied one important consequence resulted from sound propagation through a nonlinear internal wave field, 3-D sound focusing and refraction. Since the nonlinear internal wave effect is one of the causes of acoustic signal variability seen in the data, it needs to be thoroughly investigated before we can develop an adequate scheme to reduce the inversion uncertainties caused by this effect.

This part of work is in fact collaboration with many PI’s in other projects, which involves the SW06 project with Dr. James F. Lynch, Dr. Timothy F. Duda of the Woods Hole Oceanographic Institution and Dr. Mohsen Badiey of the University of Delware, and the SCS2007 NLIWI [3] project with Dr. D. Benjamin Reeder of the Naval Postgraduate School.

RESULTS

The results drawn from the work described above are summarized here.

(1) U. Miami sound source localization

We have found that that the small time-scale (< 2 min) variability in the source range estimates are due to nonlinear internal waves, as the peaks of the standard deviations perfectly correlate with nonlinear internal wave events, see Figure 6. In addition, because the water column moorings were separated by

~10 km from each other and yielded a spatial Nyquist sampling rate of 20 km, the environmental model that is constructed from the mooring data may not properly describe the water-column variability of wavelength less than 20 km. As a result, the reconstructed environmental model has water column mismatch and causes the larger time-scale variability seen in the range estimates.

(2) Sei whale localization

The ability to passively track calling sei whales in the SW06 region will enable a novel study of (1) the individual "distinctiveness" of sei whale downsweep calls and (2) the social context in which calling behavior takes place. Further collaboration to looking into this problem has been initiated with Dr. Mark Baumgartner of the Woods Hole Oceanographic Institution.

(3) Statistical merging of data sources to estimate full water-column sound speed in the SW06 experiment

The EOF fitting method has general practicality, and its advantages are summarized here. It has been shown that the water layer structure measured by one partial depth system can be accurately preserved in the merged profiles at another location in a spatially stationary region. The arrival time differences of internal waves at the two locations can be systematically and automatically compensated for without knowing exact internal wave propagation speeds and directions, see an example shown in Figure 7. Finally, the merged profiles provide a more complete oceanographic view of the local water-column variability. This is beneficial to connecting the acoustic fluctuations with the environmental changes.

(4) 3-D acoustic effects of internal waves

For an acoustic source located in an internal wave duct and sufficiently far from the termination, some of the propagating sound may penetrate the internal wave "wall" at high grazing angles, but a fair amount of the sound energy is still trapped in the duct. Due to the curvature of the internal waves, the trapped sound may not be able to follow the duct, and we have found that some ducted energy may penetrate the curved duct and form intensive beams. Whispering gallery effects may also been seen when the source and receiver both are on the same side of the exterior area in a ducting environment. In a truncated wave situation, the trapped sound will propagate towards the termination and radiate outward to form significant horizontal beams. These beams are found to be associated with individual vertical modes from both the analytical expressions and numerical calculations, as well as being confirmed by the SW06 data.

IMPACT/APPLICATIONS

The most important impact of this project is to increase the capability of underwater acoustic inversion and source localization techniques in a randomly fluctuating shallow-water ocean. Also, the data nullspace projection method and the normal mode back-propagation method developed in this project can be applied to many sonar systems.

RELATED PROJECTS

This postdoctoral fellowship is under the supervision of Dr. James F. Lynch at Woods Hole Oceanographic Institution. The acoustic and oceanographic data used in this project are collected from the ONR sponsored SW06 experiment. The PI is also working on the Quantifying, Predicting and

Exploiting Uncertainty (QPE) project to quantitatively understand the uncertainties observed in low frequency (100-1000Hz) acoustic propagation.

REFERENCES

[1] A.E.Newhall, T.F. Duda, K. von der Heydt, J.D. Irish, J.N. Kemp, S.A. Lerner, S.P. Libertatore, Y-T Lin, J.F. Lynch, A.R. Maffei, A.K. Morozov, A Shmelev, C.J. Sellers, and W.E. Witzell, Acoustic and Oceanographic Observations and Configuration Information for the WHOI Moorings from the SW06 Experiment, WHOI Technical Report WHOI-2007-04 (May 2007)

[2] P. F. J. Lermusiaux, P. J. Haley, Jr., W. G. Leslie, O. Logoutov, A. R. Robinson, Real-time forecasts and re-analyses for the Autonomous Wide Aperture Cluster for Surveillance (AWACS-06) exercise in the Middle Atlantic Bight Shelfbreak Front and Hudson Canyon region, http://mseas.mit.edu/archive/AWACS/index_AWACS.html (2006)

[3] D. B. Reeder, T. F. Duda, and B. Ma., “Short-Range Acoustic Propagation Variability on a Shelf Area with Strong Nonlinear Internal Waves,” Oceans’08 (Kobe) Conference Proceedings, IEEE (2008)

PUBLICATIONS

Lin, Y.-T, T.F. Duda and J.F. Lynch, “Acoustic mode radiation from the termination of a truncated nonlinear internal gravity wave duct in a shallow ocean area”, *J. Acoust. Soc. Am.*, vol. 126, pp. 1752-1765 (2009) [published, refereed]

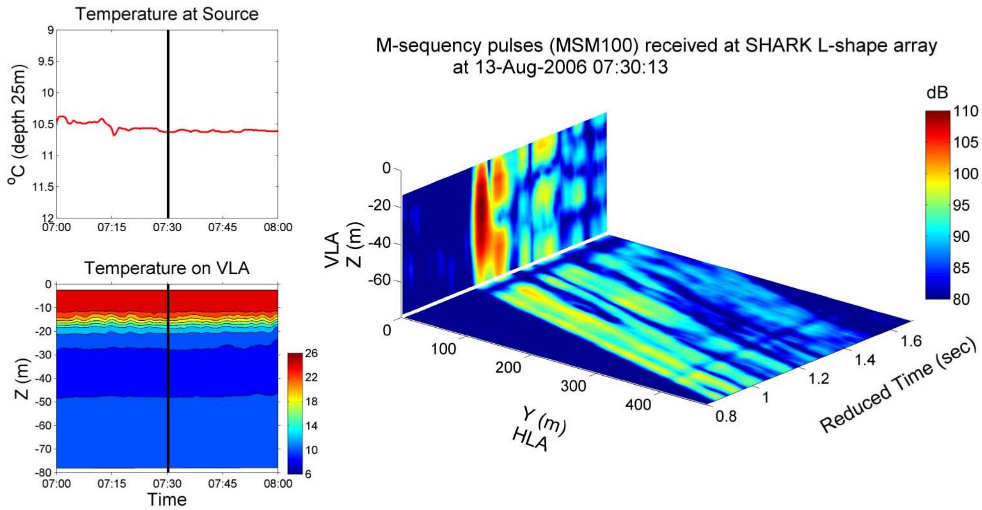
Lin, Y.-T., A.E. Newhall, T.F. Duda, P. Lermusiaux, “Merging data sources for full water column sound speed estimation in the New Jersey Shallow Water 2006 experiment”, submitted *IEEE J. Ocean. Eng.* (2009) [under review, refereed]

Lynch, J.F., Y.-T. Lin, T.F. Duda, A.E. Newhall, “Acoustic Ducting, Shadowing, Refraction and Dispersion by Curved Non-Linear Internal Waves in Shallow Water”, submitted *IEEE J. Ocean. Eng. (2009)* [under review, refereed]

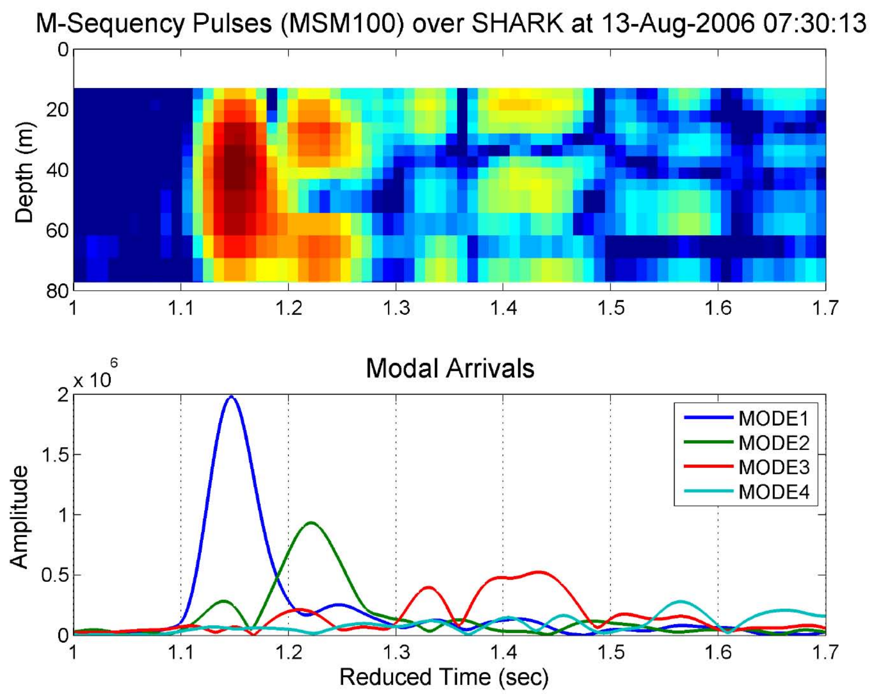
Lin, Y.-T, James F. Lynch, and Timothy F. Duda, “Investigation of the impact of water column variability on acoustic inversions in a shallow water ocean (A)”, *J. Acoust. Soc. Am.*, vol. 125, pp. 2510 (2009) [published, non-refereed]

A. E. Newhall, Y.-T. Lin, J. F. Lynch, and M. F. Baumgartner, “Sei whale localization and vocalization frequency sweep rate estimation during the New Jersey Shallow Water 2006 experiment (A)”, *J. Acoust. Soc. Am.*, vol. 125, pp. 2738 (2009) [published, non-refereed]

J. F. Lynch, Y.-T. Lin, T. F. Duda, A. E. Newhall, and G. Gawarkiewicz, “Acoustic ducting, refracting, and shadowing by curved nonlinear internal waves in shallow water (A)”, *J. Acoust. Soc. Am.*, vol. 125, pp. 2591 (2009) [published, non-refereed]



(a)



(b)

Figure 1: (a) an example of a 100-Hz M-sequence pulse reception and (b) detailed modal arrivals resulting from a least squares mode filter in the SW06 experiment

[The M-sequence pulses were transmitted from the U. Miami sound source (MSM), which was located 19.74 km northeast (25.73º due North) away from the VLA. The compressed pulses are obtained from a matched filter. Using a least squares mode filter results in a clear modal arrival pattern.]

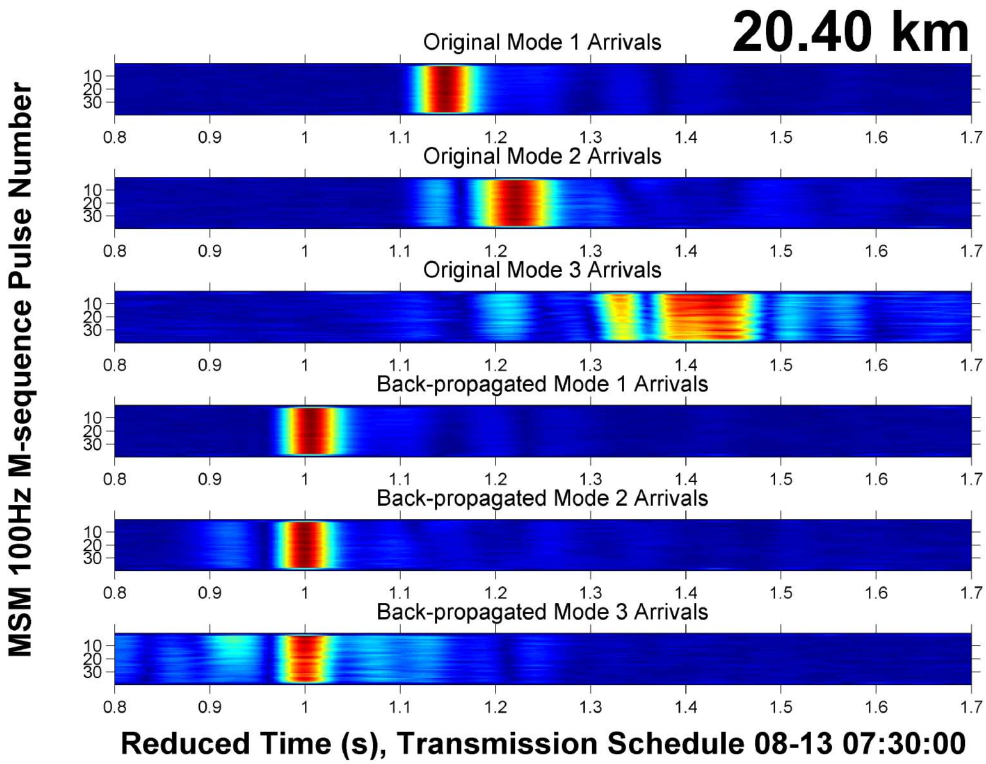
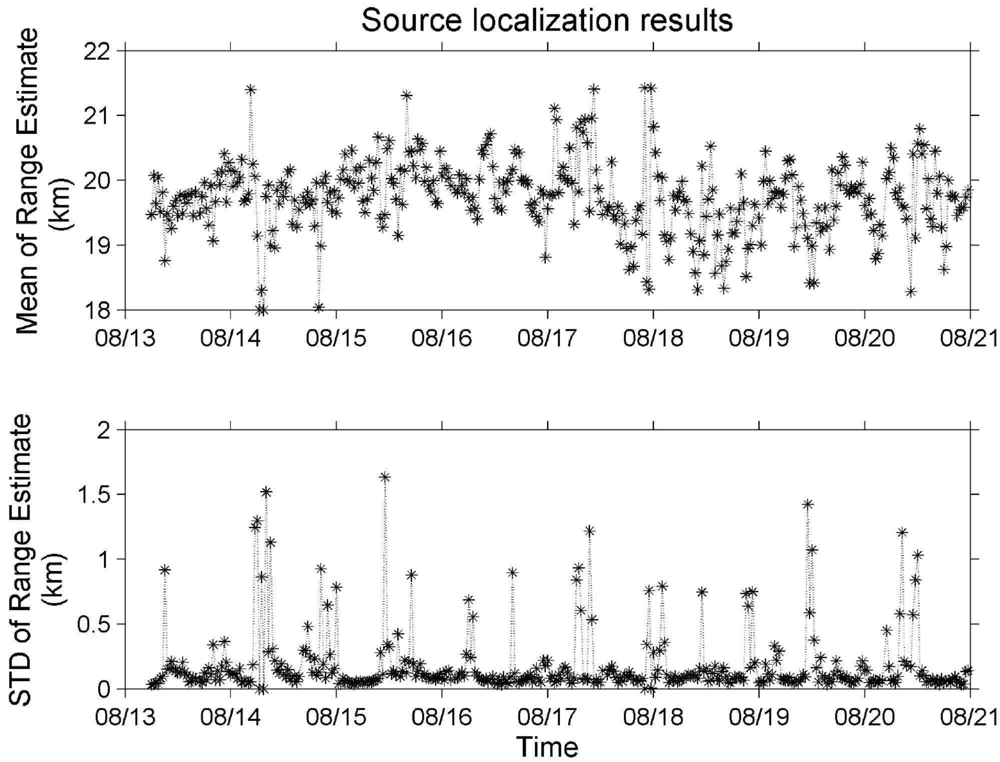
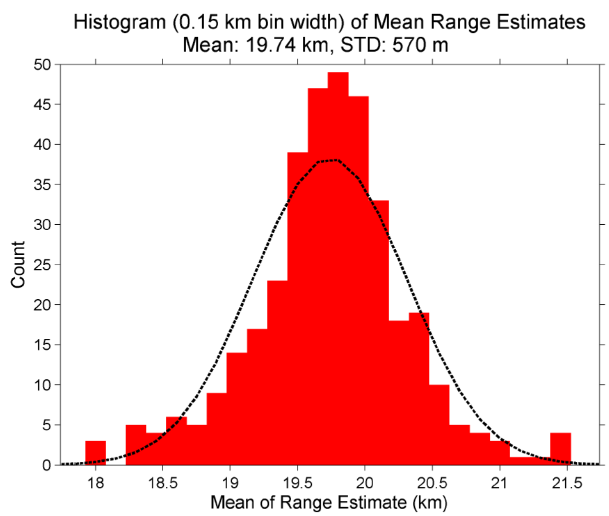


Figure 2. An example of normal mode back-propagation to find the best source range estimate.



(a)



(b)

Figure 3. MSM source localization results

[Panel (a) shows range estimates over 8 days. Every half an hour, 35 M-sequence pluses are analyzed and 35 range estimates are obtained. The average value and standard deviation of these estimates are plotted. The total mean range estimate is 19.74 km for these 8-days data, which is the same as the true distance, along with a standard deviation of 570 m. Panel (b) shows the histogram of the average range estimates.]

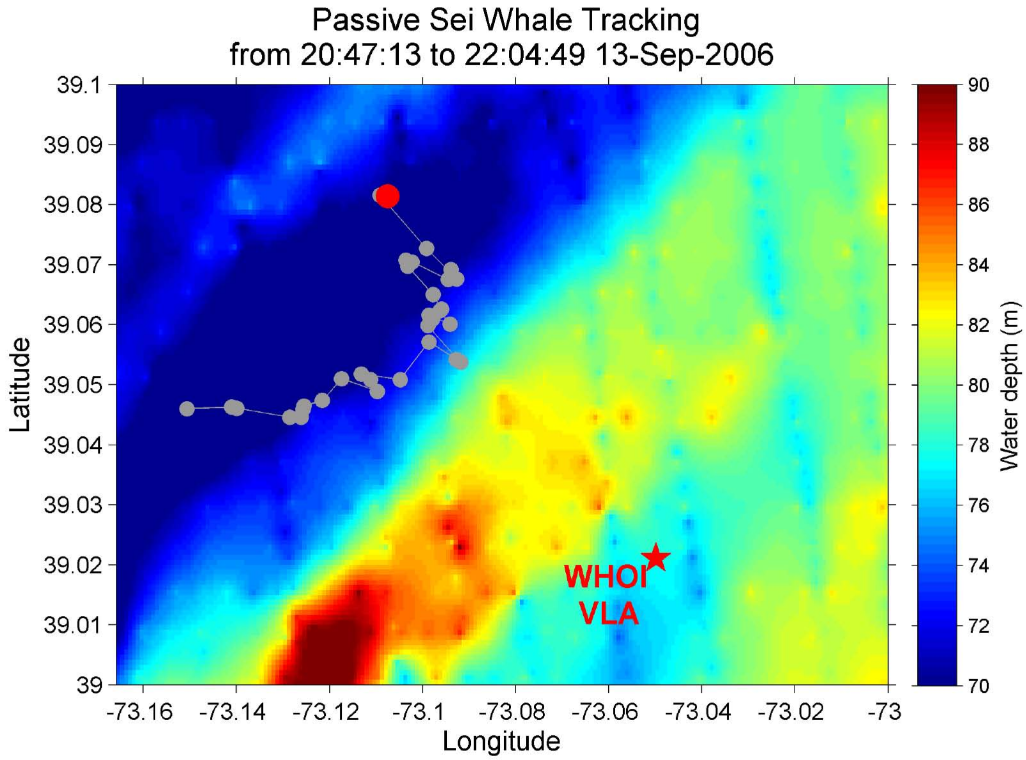


Figure 4. Estimated sei whale track from 22:47 to 22:05 on Sep 13 2006 in the SW06 experiment.

[The red star is the position of the WHOI VLA/HLA and the dots are the whale locations. The red dot is the last whale location.]

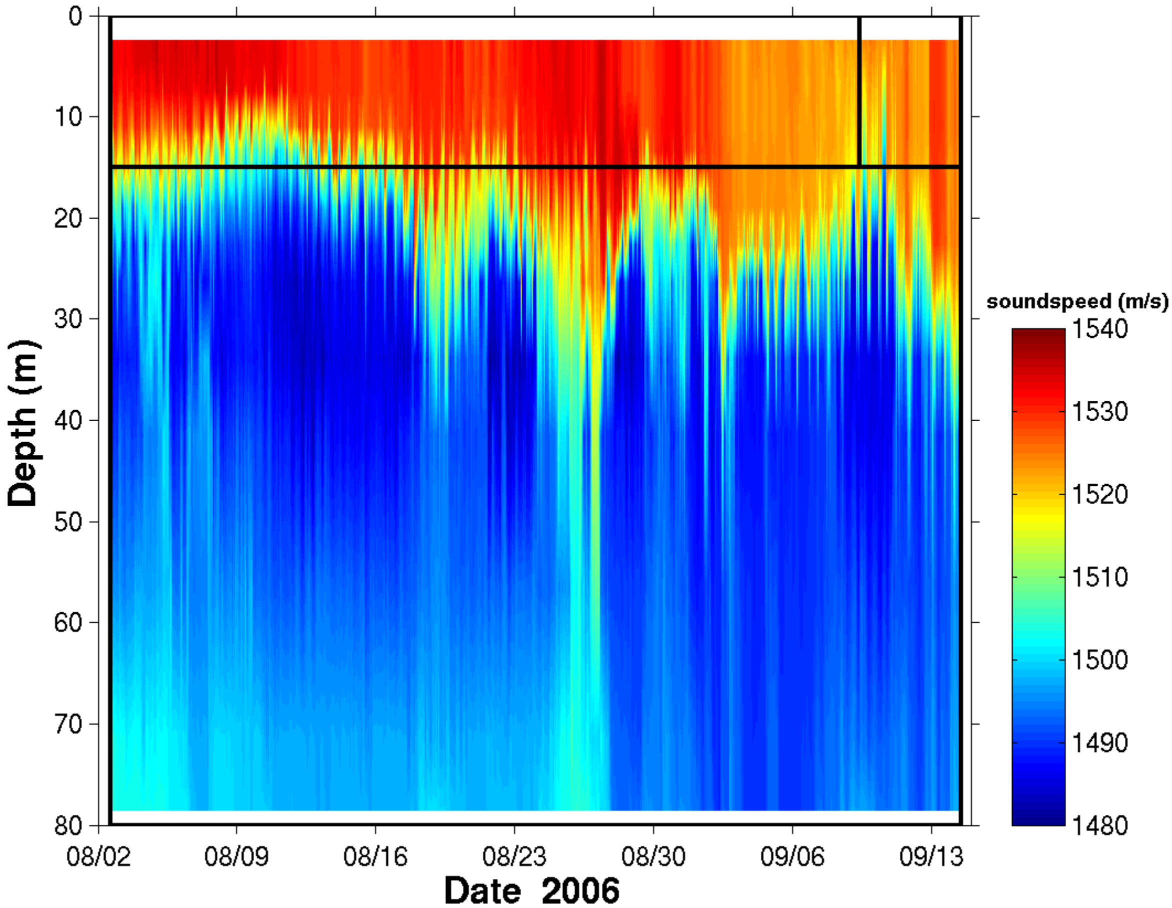


Figure 5. Full water-column sound speed profiles resulting from merging multiple data sources around and on the main VLA in the SW06 experiment.

[Boxes identify areas of different temperature data sources. The upper left box indicates the ASIS surface buoy data, the upper right one is the MSEAS ocean model results and the lower big box is the WHOI VLA data. An additional data set from anther nearby mooring is also used for incorporating salinity, along with some assistance from MSEAS ocean model results.]

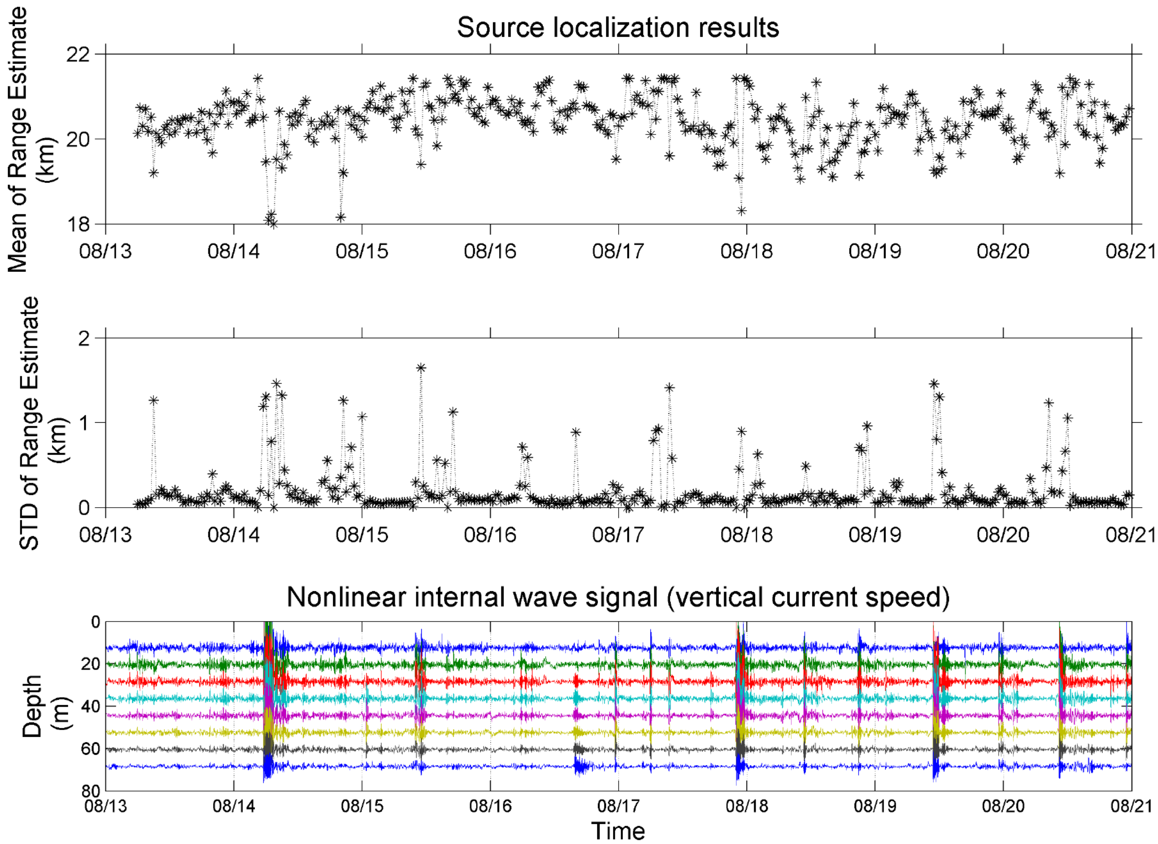


Figure 6. The MSM source localization results and the nonlinear internal wave signal (vertical current speed) observed on the mooring in the middle of the propagation path.

[The peaks of the standard deviations correlate with nonlinear internal wave events perfectly, indicating the waves are responsible to the short time-scale (< 2 min) variability.]

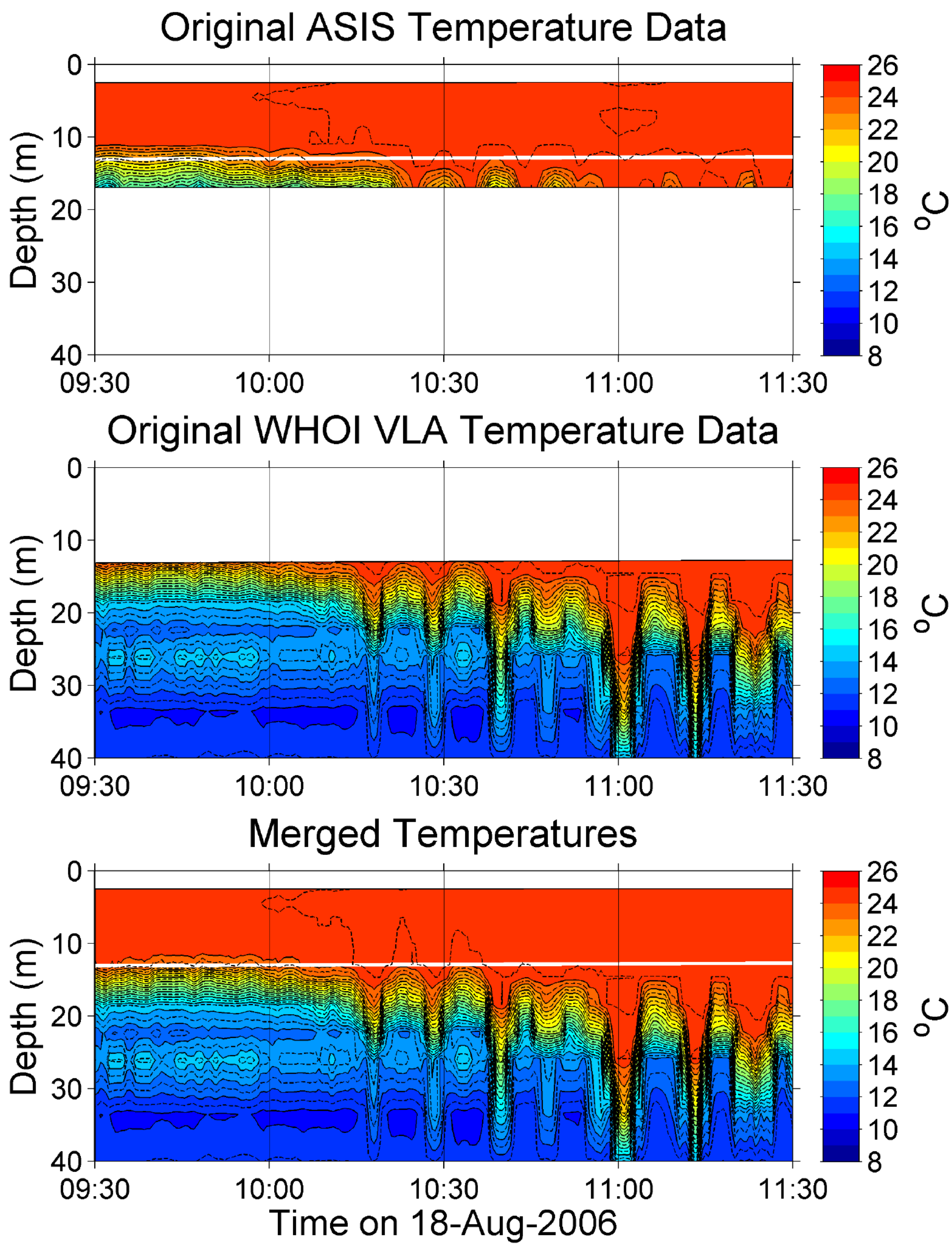


Figure 7. Contour plots of the original temperature data and the merged profiles during one large internal wave event in the SW06 experiment.

[The EOF fitting technique developed in this project is employe. It preserves the mixed layer structure measured by the ASIS surface buoy in the merged profiles, and the arrival time differences of the nonlinear internal waves are automatically adjusted. Contour level increment is 1 degree in colors and 0.5 degree in lines.]